The effect of averaging adjacent planes for artifact reduction in matrix inversion tomosynthesis

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Purpose: Matrix inversion tomosynthesis (MITS) uses linear systems theory and knowledge of the imaging geometry to remove tomographic blur that is present in conventional backprojection tomosynthesis reconstructions, leaving in-plane detail rendered clearly. The use of partial-pixel interpolation during the backprojection process introduces imprecision in the MITS modeling of tomographic blur, and creates low-contrast artifacts in some MITS planes. This paper examines the use of MITS slabs, created by averaging several adjacent MITS planes, as a method for suppressing partial-pixel artifacts.

Methods: Human chest tomosynthesis projection data, acquired as part of an IRB-approved pilot study, were used to generate MITS planes, three-plane MITS slabs (MITSa3), five-plane MITS slabs (MITSa5), and seven-plane MITS slabs (MITSa7). These were qualitatively examined for partial-pixel artifacts and the visibility of normal and abnormal anatomy. Additionally, small (5 mm) subtle pulmonary nodules were simulated and digitally superimposed upon human chest tomosynthesis projection images, and their visibility was qualitatively assessed in the different reconstruction techniques. Simulated images of a thin wire were used to generate modulation transfer function (MTF) and slice-sensitivity profile curves for the different MITS and MITS slab techniques, and these were examined for indications of partial-pixel artifacts and frequency response uniformity. Finally, mean-subtracted, exposure-normalized noise power spectra (ENNPS) estimates were computed and compared for MITS and MITS slab reconstructions, generated from 10 sets of tomosynthesis projection data of an acrylic slab. The simulated in-plane MTF response of each technique was also combined with the square root of the ENNPS estimate to yield stochastic signal-to-noise ratio (SNR) information about the different reconstruction techniques.

Results: For scan angles of 20° and 5 mm plane separation, seven MITS planes must be averaged to sufficiently remove partial-pixel artifacts. MITSa7 does appear to subtly reduce the contrast of high-frequency “edge” information, but the removal of partial-pixel artifacts makes the appearance of low-contrast, fine-detail anatomy even more conspicuous in MITSa7 slices. MITSa7 also appears to render simulated subtle 5 mm pulmonary nodules with greater visibility than MITS alone, in both the open lung and regions overlying the mediastinum. Finally, the MITSa7 technique reduces stochastic image variance, though the in-plane stochastic SNR (for very thin objects which do not span multiple MITS planes) is only improved at spatial frequencies between 0.05 and 0.20 cycles/mm.

Conclusions: The MITSa7 method is an improvement over traditional single-plane MITS for thoracic imaging and the pulmonary nodule detection task, and thus the authors plan to use the MITSa7 approach for all future MITS research at the authors’ institution. © 2013 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4773891>]

Key words: tomosynthesis, three-dimensional imaging, NPS, MTF, chest, radiography, pulmonary nodule, simulated nodule

I. INTRODUCTION

It has been shown that human detection performance in standard 2D projection radiographic images of the chest is substantially hindered by the visual complexity of thoracic

anatomy.¹ This background “clutter” is greatly simplified in 3D imaging techniques, which separate overlying anatomy in a 3D volume into distinct tomographic slices. Tomosynthesis is a quasi-3D imaging technique which is effective at providing many of the benefits of a fully 3D modality,

such as computed tomography (CT), but with easy adaptation to conventional radiographic imaging environments and with lower cost and radiation dose than CT.^{2,3} Preliminary investigations into the use of tomosynthesis for chest imaging suggest that tomosynthesis is significantly superior to conventional radiographic imaging for the detection of both pulmonary nodules⁴⁻⁸ and pulmonary mycobacterial lesions.⁹

Anatomic detail in conventional backprojection (shift-and-add) tomosynthesis is obscured by tomographic blur from structures located outside the plane of interest. Matrix inversion tomosynthesis (MITS) uses linear systems theory along with knowledge of the imaging geometry to deterministically separate true in-plane detail from residual tomographic blur, and thereby render anatomy with improved displayed contrast and conspicuity.¹⁰

In a previous paper,¹¹ we used simulated impulse response (IR) and modulation transfer function (MTF) characteristics to conclude that the optimal MITS imaging strategy for thoracic tomosynthesis on our prototype system entails the collection of 71 projections (NPROJ) over a total scan angle (ANG) of 20°, and the reconstruction of 69 planes (NP). In another paper,¹² we examined the stochastic noise properties in MITS planes by measuring and comparing exposure-normalized noise power spectra (ENNPS) for a variety of MITS imaging techniques, and concluded that planes reconstructed with the optimized MITS technique exhibit acceptable stochastic characteristics.

This paper will examine a simple, yet effective slice-averaging method¹³ for suppressing low-contrast low-frequency artifacts which arise from nonlocal structure in MITS planes due to digitization during the modeling of MITS blurring functions. Slice averaging is often performed in CT imaging to reduce stochastic noise, but tomosynthesis imaging inherently produces relatively thick slices with good stochastic properties. Thus, the primary motivation for averaging MITS planes is the removal of deterministic artifacts that are very specific to MITS, though modest stochastic noise reduction is an expected ancillary benefit. In this study, three, five, and seven-plane slabs, formed by averaging adjacent MITS planes, are compared with the original single-plane MITS technique. The presence of digitization artifacts, impact on effective slice thickness, and qualitative rendering of normal anatomy is compared for each technique using simulated MTF data and human thoracic MITS reconstructions. From these results, we select an optimal number of planes for slab reconstructions.

To evaluate any potential ancillary stochastic noise benefit from the selected slice averaging technique, the stochastic noise properties of the optimal MITS slab and single-plane MITS techniques are compared using measured ENNPS data. Finally, to ensure that slice averaging does not negatively impact the visibility of small lesions due to volume averaging effects, the qualitative visibility of simulated pulmonary nodules in MITS and MITS slab thoracic reconstructions of a human subject is investigated.

The optimal technique, determined from this study, was used in a NIH-sponsored trial to evaluate digital chest tomosynthesis for improving the detectability of small lung

nodules, and initial published results show that the method significantly improves nodule detectability compared to traditional radiographic imaging.⁴

II. BACKGROUND

II.A. MITS overview

The MITS algorithm has been described in previous literature.^{4,12-18} The focus of the method is an attempt to separate true in-plane detail from undesirable tomographic blur in a set of conventional tomosynthesis (also known as “shift-and-add” or backprojection) reconstructed planes, oriented parallel to the image receptor. MITS models the conventional tomosynthesis blurring process by introducing a set of impulse response functions which describe how detail in each plane is blurred onto all of the other tomosynthesis planes during the backprojection process. The blur in each plane is then deterministically removed in the Fourier domain through a series of simple matrix inversion and linear algebra operations, ideally leaving only the true unblurred in-plane structures.

Noise amplification at the very lowest spatial frequencies in MITS planes is a direct result of reduced matrix conditioning at these frequencies during the matrix inversion operation. This is compensated for by replacing a portion of the lowest MITS spatial frequencies with corresponding conventional tomosynthesis spectra, using a procedure outlined previously.¹²

Resulting MITS planes demonstrate reduced slice thickness,¹¹ particularly at low and mid spatial frequencies, even when using narrow scan angles, as well as a reduction in the overabundance of low-frequency tomographic blur that obscures information in conventional tomosynthesis reconstructions.

II.B. Partial-pixel artifacts from sampled image data

Although MITS theoretically solves for in-plane detail when projection and conventional tomosynthesis images are continuous and noise-free, the sampling inherent to digital imaging leads to imprecise modeling of the blurring functions in the MITS algorithm. In practice, the conventional tomosynthesis blur is modeled by tracking the blurring of Kronecker delta functions located at each of the depths of the planned reconstruction set. Only a single delta function is necessary for each depth, as the geometry of linear tomosynthesis is such that the ideal blurring functions are shift-invariant within any single plane, neglecting digital sampling effects. Each delta function is forward-projected onto an imaginary image receptor, according to the assumed imaging geometry for each projection angle, and then backprojected during the creation of each of the conventional tomosynthesis planes. As the impulse projections and backprojections rarely fall exactly in the center of a pixel or voxel, they are split at each step via linear interpolation. The resulting array describes how signals originating from objects in each plane bleed through onto each other plane in the conventional tomosynthesis reconstruction set (i.e., it describes the expected tomosynthesis blur).

FIG. 1. MITS upper left lung ROI from a human subject, reconstructed using two different alignments of the MITS blurring functions with the image matrix. Black arrows point to low-contrast, nonlocal rib artifacts that appear in different patterns depending upon the presumed alignment.

However, the exact form of the resampled blurring functions depends upon the assumed alignment of the system of impulses with the image pixel and object voxel grid, as well as the specific depths of each of the reconstructed planes. We might, for example, assume an alignment such that, for all tomosynthesis planes, the point sources used to create the MITS blurring functions fall exactly in a pixel center in the central projection image. For all other projections and plane depths, the alignment of impulses with the image grid will be determined by the relative shifts created during the projection and backprojection process. Conversely, we might just as well assume that point sources are projected such that they fall between pixel centers in the central projection image. Using linear interpolation, the net result is a slightly different rendition of the MITS blurring functions in each example.

Imprecise modeling of partial-pixel effects leads to low-contrast artifacts from distant planes in some reconstructed MITS planes. Figures 1(a) and 1(b) shows a region of interest (ROI) in the upper left lung from the same centrally located MITS plane of a human subject, reconstructed with the same projection data but two different subjective alignments of impulse response functions with the image array. No difference is observed in the rendering of in-plane anatomy, but each image is degraded by different patterns of low-contrast artifacts (indicated by black arrows) that originate from the distant posterior ribs, illustrating how only shifting the sampling of the MITS blurring functions strongly varies the pattern and presence of the artifacts in question. We refer to these artifacts as partial-pixel artifacts since they arise from the partial-pixel interpolation used when modeling the MITS impulse response.

Figure 2 illustrates the large extent to which the magnitude of partial-pixel artifacts can vary in two adjacent MITS planes from the same reconstruction set.

II.C. Artifact suppression

Several attempts at correcting for partial-pixel artifacts in MITS reconstructions have been made. Performing sinc interpolation rather than linear interpolation during conventional tomosynthesis reconstruction requires additional com-

FIG. 2. Two adjacent MITS planes from a single MITS reconstruction of an anthropomorphic chest phantom exhibit very different partial-pixel artifact effects, despite being separated by only 5 mm depth. The plane in image (a) shows very little evidence of the artifacts, while the plane in image (b) is strongly impacted.

putation, and initial trials in our laboratory have not proven it effective in reducing all MITS artifacts. Averaging MITS reconstructions with varying alignments between the blurring function and image pixel grid has resulted in some improvement, but has also not demonstrated full suppression of the artifacts in question.

A simpler artifact suppression method entails the averaging of several adjacent MITS planes to create MITS slab images. This approach creates overlapping slabs centered about each original MITS plane, except the most anterior and posterior MITS planes, where adjacent planes do not exist. (For example, a MITS slab cannot be centered about the most anterior MITS plane, as no adjacent MITS plane exists anterior to the central plane in the slab.)

The MITS slab technique takes advantage of the fact that partial-pixel artifacts vary greatly in location and intensity amongst adjacent MITS planes, while true local detail tends to be shared to some degree across multiple planes. Stacking multiple adjacent slices averages over the shifting artifacts, but has much less effect on the contrast of the stationary true anatomy. Furthermore, there are likely noise benefits from the slab procedure, as averaging several planes ought to reduce stochastic image variance.

Note: Due to some similarity in low frequency content amongst adjacent MITS planes, the magnitude of low frequency conventional tomosynthesis spectra that is added back to the MITS reconstructions for noise suppression (discussed in previous literature³) is reduced by 50% when forming MITS slabs, but no other additional processing differences exist between single-plane MITS and the MITS slab methods.

III. METHODS

III.A. Evaluation of human chest tomosynthesis images

Human tomosynthesis projection data were acquired with a prototype chest tomosynthesis system,¹⁷ which includes an x-ray tube, commercial flat-panel detector (41×41 cm²; 0.2 mm pitch; RevolutionTM; GE Medical Systems, Milwaukee WI), prototype rapid-readout electronics which allow a maximum frame-rate of 6.4 frames/s, and custom motion hardware which moves the x-ray tube in a continuous sweep

along a vertical path parallel to the detector. The impact of tube motion blur during individual exposures, robustness of MITS to uncertainty in the source-detector geometry, and effect of detector image retention on MITS image quality, are thoroughly discussed in a previous publication,¹⁷ and have been shown to be minimal. The prototype was constructed “in house,” and thus the hardware and reconstruction software differs considerably from the final commercial version later released by GE Medical Systems (VolumeRAD™).

A subjective analysis of the efficacy of the MITS slab technique was conducted on the thoracic tomosynthesis data (ANG = 20°, $N = 61$) of one human subject, acquired with the prototype experimental system as part of an IRB-approved pilot study. Cumulative exposure during the tomosynthesis procedure was held roughly equivalent to that of two 250-speed screen/film lateral radiographs. All projection images were acquired during a single breath-hold, spanning roughly 11 s. A posterior-anterior (PA) radiograph was also acquired with the prototype system as part of the study.

MITS, MITSa3, MITSa5, and MITSa7 chest reconstructions (plane separation [PSEP] = 5 mm) of the human subject were subjectively evaluated for the presence of partial-pixel artifacts and overall anatomic visibility.

III.B. Simulated modulation transfer functions and slice sensitivity profiles

To quantitatively evaluate the impact of slice averaging on partial-pixel artifacts and effective slice thickness, a linear systems analysis of the response of the four reconstruction techniques to both in-plane and off-plane signals was performed using simulations of their IR functions in the spatial domain and MTF in the frequency domain. The simulated MTF data were normalized to their maximum (described below) and transformed into slice sensitivity profiles (SSP) for individual frequencies, to evaluate the impact of the slice averaging techniques on both the uniformity of the effective slice thickness across different frequencies and the suppression of nonlocal low frequency partial-pixel artifacts.

Using a previously published method,¹¹ IR data were created by simulating the response of MITS and MITS slabs to a thin wire running horizontally, with varying depth (z , or distance from the detector), through the image-space. 71 equally spaced, noise-free projection images of the simulated object were generated, assuming 20° of vertical linear motion of the x-ray tube and a diverging-beam x-ray source. An illustration of the simulated imaging space is displayed in Fig. 3.

MITS, MITSa3, MITSa5, and MITSa7 reconstructions were created using the simulated projection data, for a total reconstruction depth of 300 mm and a plane spacing of 4.4 mm. Thus, for MITS, NP = 69; MITSa3, NP = 67; MITSa5, NP = 65; and MITSa7, NP = 63 (NP = number of reconstructed planes). As seen in Fig. 3, each column of the simulated image space contains a single impulse (section of the wire) located at a specific distance from the image receptor, which varies from one column to the next. Thus, MITS planes reconstructed parallel to the receptor intersect the wire

FIG. 3. Wire simulation geometry for vertical tube movement. Reproduced by permission from Godfrey *et al.*, Med. Phys. **33**, 655–667 (2006).

in only one column, yielding the in-plane impulse response. All other columns in MITS planes contain off-plane impulse responses at varying depths, revealing the manner in which distant information bleeds through onto a specific MITS plane (i.e., the tomosynthesis “blur”). A sample 3D representation of the reconstructed impulse response in a central MITS plane is displayed in Fig. 4, highlighting the strong in-plane response and good suppression of out-of-plane information.

The magnitude of the 1D Fourier transform for each column of the simulated MITS IR data was computed to convert the impulse responses into vertical frequency MTFs as a function of depth (i.e., distance from the image receptor). Resulting MTF “images” therefore show the response of a single tomosynthesis slice to varying vertical spatial frequencies (vertical image axis) and signal origination depths (horizontal image axis), as illustrated in the sample MTF image of Fig. 5.

The in-plane MTF response of each of the reconstruction techniques was evaluated by viewing MTF image columns whose impulse depth coincided with the depth of the reconstruction plane or slab, while the out-of-plane response was

FIG. 4. 3D rendering of a sample simulated MITS impulse response function, showing a strong in-plane peak, with weaker residual off-plane tomosynthesis blur. Reproduced by permission from Godfrey *et al.*, Med. Phys. **33**, 655–667 (2006).

FIG. 5. Simulated normalized MTF image for a MITS plane located at a depth of 156 mm from the image receptor. A solid arrow (upper right) points to nonlocal low-frequency artifacts resulting from partial-pixel interpolation. A dashed arrow (lower right) points to nonlocal high-frequency artifacts that arise when too few projections are used to sample the tomosynthesis scan angle (Ref. 11) unrelated to the partial-pixel effect.

evaluated for each frequency according to the information contained in each corresponding row of the MTF images.

For any specific spatial frequency, the maximum tomosynthesis MTF response is generally expected to occur at the exact depth of the slice center. However, the variable nature of partial-pixel interpolations often slightly degrades the magnitude of the in-plane MTF, resulting in MTF maxima that are very slightly offset from the exact plane depth. To account for this, normalized MTF (NMTF) data were created by dividing each MTF image row (representing the response to a single vertical spatial frequency) by its maximum value, ensuring that the magnitude of distant off-plane frequency content was always properly benchmarked against the maximum magnitude rendered by the plane. These NMTF data were employed to analyze the MITS and MITS slab techniques for the presence of nonlocal low-frequency information attributable to partial-pixel effects.

Slice sensitivity profiles¹¹ were generated by extracting rows from the NMTF images, yielding the NMTF as a function of depth, for any fixed vertical spatial frequency. For this study, SSPs were created for MITS and MITS slab reconstructions, for six vertical spatial frequencies ($v = 0.05, 0.10, 0.25, 0.50, 0.75$, and 1.25 cycles/mm), for a plane located 156 mm from the image receptor, a depth representative of the central lung region in thoracic tomosynthesis imaging. These were viewed both for the presence of partial-pixel artifacts as well as for the effective slice thickness generated by each reconstruction algorithm.

III.C. Exposure-normalized noise power spectra

To evaluate any potential stochastic noise benefit in MITS slab reconstructions, we computed the exposure-normalized noise power spectra in mean-subtracted MITS planes and MITS slabs from tomosynthesis scans with $ANG = 20^\circ$, $N = 71$, $NP = 69$, $PSEP = 4.4$ mm, using a previously published method.¹²

Ten sets (realizations) of tomosynthesis projection data (710 total images) were collected with the experimental pro-

totype system described in Sec. III.A, using the standard technique employed when imaging human subjects, including 120 kVp, 0.2 mm added Cu filtration, and an antiscatter grid (13:1, 78 lp/cm). An 11.4 cm acrylic slab was placed directly in front of the detector assembly to roughly mimic beam hardening and scatter characteristics of the lung, which is assumed to typically have a tissue equivalent thickness of approximately 10 cm. Cumulative tube output for each tomosynthesis scan was 56.8 mAs.

MITS and MITS slab reconstructions were generated from each of the ten projection datasets. The ten realizations of each reconstructed plane/slab were averaged and then subtracted from each individual realization to create mean-subtracted MITS and MITS slab data. This step effectively removed fixed patterns arising from nonstochastic processes such as pixel gain differences, and artifacts arising from the antiscatter grid, ensuring that the remaining images were composed almost entirely of stochastic noise.

A 4×7 arrangement of ROIs (128×128) was extracted from the center of each 1024×1024 mean-subtracted slice image and used for NPS estimation. 2D NPS estimates were generated by averaging the square of the magnitude of the 2D FFTs from each ROI, after normalization to account for ROI and pixel size:

$$NPS(u, v) = COR \cdot \frac{\langle |FT(u, v)|^2 \rangle}{NPIX_x NPIX_y} \cdot \Delta x \Delta y, \quad (1)$$

where $\langle |FT(u, v)|^2 \rangle$ is the ensemble average of the squared Fourier magnitudes across all ROIs, $NPIX_x$ and $NPIX_y$ are the dimensions of the discrete 2D Fourier transform (i.e., the ROI dimensions), and Δx and Δy are the horizontal and vertical pixel pitch of the flat-panel detector. COR refers to the mean-subtraction correction factor, which accounts for the fact that the estimate of image variance in a mean-subtracted image is artificially reduced because the mean image contains some of the stochastic information from the individual image realization:

$$COR = \frac{NREAL}{NREAL - 1}, \quad (2)$$

where NREAL is the number of datasets (realizations) used to create mean images for the mean-subtraction step. For this study, $NPIX_x = NPIX_y = 128$, $\Delta x = \Delta y = 0.4$ mm, $NREAL = 10$, and $COR = 10/9$.

Noise power in the vertical spatial frequencies, $NPS(v)$, were extracted from the 2D $NPS(u, v)$ estimates for each mean-subtracted slice by averaging the nearest 4 columns on both sides of the v -axis, while excluding the v -axis itself.¹⁹ Finally, the ten $NPS(v)$ realizations for each slice location were averaged to create our final NPS estimate for each reconstructed plane/slab.

In keeping with our previous methodology for NPS estimation in tomosynthesis data,³ NPS estimates in this study were multiplied by measured exposure to generate ENNPS estimates, which are independent of differences in incident exposure. An exposure meter placed where the center of the x-ray beam crosses the plane of the detector measured a

cumulative tomosynthesis exposure of 84.5 ± 0.1 mR over three scans. Thus,

$$\text{ENNPS}(v) = \text{NPS}(v) \cdot 84.5 \text{ mR} \quad (3)$$

for the data in this study.

III.D. Stochastic signal-to-noise ratio

To evaluate the joint impact of plane averaging on effective slice thickness and stochastic noise, the MTF and noise power data were combined into a signal-to-noise figure of merit. Specifically, the effect of averaging MITS planes on the stochastic signal-to-noise ratio (SNR) was examined by computing the ratio of MITS-slab to single-plane MITS figures for in-plane MTF and the square root of the ENNPS. Spatial frequency regions where the in-plane MTF ratio was larger than the $\text{ENNPS}^{0.5}$ ratio were considered to have improved stochastic SNR due to the formation of MITS slabs, while frequency regions whose MTF ratio was less than the corresponding $\text{ENNPS}^{0.5}$ ratio were deemed to have degraded stochastic SNR.

III.E. Simulated subtle pulmonary nodules in human chest tomosynthesis images

Finally, in light of the potential for volume averaging in the MITS slab technique, we investigated the efficacy of the MITS slab technique to adequately render small pulmonary nodules by simulating subtle pulmonary nodules in human chest tomosynthesis projection data, according to a method developed by Samei *et al.* for digitally superimposing realistic nodules in 2D chest radiographs.^{1,20,21}

The method assumes a radial nodule contrast function of the form

$$C(r) = C_p \left[\frac{4.0}{D^4} r^4 - \frac{4.2}{D^2} r^2 + 1 \right] \quad (4)$$

in log-transformed projection data, where r is the radial distance in mm, C is the contrast, C_p is the peak nodule contrast (at the center of the nodule), and D is the diameter of the nodule. The relationship $-0.6D < r < 0.6D$ is enforced to limit the spatial extent of the nodule profile. Peak contrast, C_p , is computed according to the contrast-to-diameter

relationship

$$\frac{C_p}{D} = \left[\frac{\rho_n - \rho_l}{1 + R} \right] \mu_{\text{eff}}, \quad (5)$$

where $R = 0.68$ is the assumed scatter-to-primary ratio (empirically measured by Samei *et al.* for a uniform 7.62-cm slab of Lucite¹³), $\rho_n = 1.0$ g/ml is the assumed density of the nodule, $\rho_l = 0.3$ g/ml is the assumed lung density, and $\mu_{\text{eff}} = 0.0235 \text{ mm}^{-1}$ is the effective linear attenuation coefficient of nodular tissue (estimated by Samei *et al.* using an x-ray spectral model¹), in the absence of scattered radiation.

For this study, small (5 mm) simulated pulmonary nodule contrast profiles were digitally superimposed into several regions of the human subject tomosynthesis projection data described in Sec. III.A. Nodules were located in projection data according to user-selected 3D nodule-center coordinates and the projection geometry. No attempt was made to alter the symmetry of the nodule contrast profile model to account for beam divergence.

MITS and MITS slab reconstructions of slices containing the simulated nodules were examined subjectively for nodule visibility.

IV. RESULTS

IV.A. Evaluation of human chest tomosynthesis images

Figures 6(a)–6(e) show a human upper left lung ROI from a PA radiograph, and single-plane MITS, MITSa3 (1.0 cm slab), MITSa5 (2.0 cm slab), and MITSa7 (3.0 cm slab) reconstructions, respectively. All tomosynthesis renderings show substantially improved contrast of in-plane anatomy, compared with the PA radiograph ROI. Solid arrows point to partial-pixel artifacts in the single-plane MITS rendering, as well as 3 and 5-plane MITS slab images. No partial-pixel artifacts are visible in the MITSa7 reconstruction. A dashed oval in the MITSa7 slice surrounds clearly visible, finely detailed vasculature which is obscured by partial-pixel artifacts in the MITS reconstruction. Finally, a dashed arrow points to visually confounding, high-contrast, near-plane tomographic blur from anterior rib regions which are just posterior to the plane of interest in the MITS reconstruction. The MITSa7 slab does not contain such partially smeared structure, but instead

FIG. 6. Human upper left lung ROI from (a) a PA radiograph, (b) single-plane MITS, (c) MITSa3 (1.0 cm slab), (d) MITSa5 (2.0 cm slab), and (e) MITSa7 (3.0 cm slab). Solid arrows point to partial-pixel artifacts. A dashed arrow points to high-contrast tomographic blur from anterior rib regions that are just posterior to the plane of interest. An oval is drawn around a region of the MITSa7 ROI that clearly renders fine vasculature which is obscured by artifacts in the single-plane MITS image.

FIG. 7. (a) Single-plane MITS and (b) MITSa7 reconstructions through the central left lung of a human subject. A series of 1 mm calcified nodules in the apex of the lung are noted with an oval ring, while an arrow points to a calcified subcarinal lymph node.

renders the slab in sharp focus, while everything outside the slab is strongly suppressed.

Single-plane MITS and MITSa7 reconstructions through the central left lung of the human subject are displayed in Fig. 7. An oval ring surrounds a series of calcified 1 mm nodules in the apex of the lung, while an arrow points to a calcified subcarinal lymph node. The left main bronchus is

clearly visible just above the calcified lymph node in both images. Contrast and sharpness of the calcified features appears slightly reduced in the MITSa7 reconstruction, but the slab method ameliorates partial-pixel artifacts that are present in the MITS plane, and renders low-contrast fine pulmonary detail with much greater clarity.

IV.B. Simulated modulation transfer functions and slice sensitivity profiles

Figure 8 displays simulated NMTF images for (a) single-plane MITS, (b) MITSa3, (c) MITSa5, and (d) MITSa7 reconstructions located at a depth of 156 mm. The width of the main NMTF ridge appears thicker, but more uniform for MITS slabs than for the single MITS plane. Strong bands of nonlocal low-frequency content below 0.5 cycles/mm (see solid arrow) are present in the single-plane reconstruction, but gradually fade as the number of averaged planes is increased for MITS slabs. Distant low-frequency content does not appear in the MITSa7 image. On the other hand, averaging MITS planes increases the number of nonlocal high-frequency peaks [dashed arrow in Fig. 8(a)] that arise when too few projections are used to fully sample the tomosynthesis scan angle.^{10,11,17} However, the magnitude of individual nonlocal undersampling peaks is reduced by the MITS slab approach, and undersampling artifacts are not qualitatively prominent in MITS or MITS slab images with the currently employed acquisition technique.

FIG. 8. Simulated NMTF images for (a) single-plane MITS, (b) MITSa3, (c) MITSa5, and (d) MITSa7 reconstructions located at a depth of 156 mm (from the image receptor). A solid arrow points to nonlocal low-frequency partial-pixel artifacts in the single-plane MITS rendition. A dashed arrow calls attention to nonlocal high-frequency artifacts that arise when too few projections are used to sample the tomosynthesis scan angle.

FIG. 9. Simulated SSPs for six different vertical spatial frequencies in a single-plane MITS reconstruction of a plane located 156 mm from the image receptor ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm).

SSPs, made by extracting rows from NMTF images, are shown for six different frequencies in a single-plane MITS and MITSa7 slice in Figs. 9 and 10, respectively. Large peaks are present distant from the plane location in single-plane MITS SSPs for vertical spatial frequencies of 0.10 and 0.25 cycles/mm, and indicate the transfer of distant frequency content onto the plane of interest. MITSa7 SSPs show strong suppression of nonlocal artifactual information at 0.10 and 0.25 cycles/mm. The primary NMTF peak in the MITSa7 SSP curves has a fairly constant width across many frequencies, which suggests that the MITSa7 slice thickness is nearly uniform for frequencies ranging from 0.10 to 0.75 cycles/mm.

The simulated in-plane MTF for a centrally located MITS and MITSa7 slice are displayed in Fig. 11. The MITSa7 in-plane MTF curve multiplied by 7 is also plotted (labeled “7*MITSa7”) and, when compared to the MITS MTF, shows

FIG. 10. Simulated SSPs for six different vertical spatial frequencies in a MITSa7 (2.65 cm slab) reconstruction centered 156 mm from the image receptor ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm).

FIG. 11. MITS and MITSa7 simulated MTF response to a signal located at the same depth as the reconstruction plane ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm, reconstruction depth = 200.8 mm). The MITSa7 MTF is also shown multiplied by 7 to display the response of the sum (as opposed to the average) of the seven adjacent planes used to make the MITSa7 image.

where MITSa7 receives in-plane contribution from the 6 MITS planes adjacent to the central plane in the MITSa7 slab. As a whole, the six planes adjacent to the central plane of the MITSa7 slab are shown to contribute substantially to the in-plane response below 0.4 cycles/mm, and subtly augment the response up to 0.8 cycles/mm.

IV.C. Exposure-normalized noise power spectra

Figures 12(a) and 12(b) show the ENNPS for all planes in a MITS and MITSa7 reconstruction, respectively ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm). The MITSa7 technique substantially reduces image variance, as expected, particularly at low frequencies in the most anterior and posterior regions, where MITS exhibits large noise spikes.

IV.D. Stochastic signal-to-noise ratio

Plots of the ENNPS and in-plane MTF ratios for the two techniques (MITSa7 vs MITS), computed for a centrally located plane, are shown in Fig. 13. The “expected ratio” of 1/7 is also plotted to illustrate the ratio one would expect if the seven planes used to create the MITSa7 slab were stochastically and deterministically independent. For most low frequencies, from ~ 0.05 to 0.5 cycles/mm, the averaging of adjacent planes is shown to suppress stochastic variance more than the in-plane deterministic response.

Figure 14 displays MITSa7 vs MITS in-plane MTF and $\text{ENNPS}^{0.5}$ ratios, both components of any expected change in the traditional stochastic SNR figure of merit. It is evident that the stochastic SNR is only improved (MTF ratio greater than the $\text{ENNPS}^{0.5}$ ratio) by the MITSa7 technique for frequencies between 0.05 and 0.2 cycles/mm, and is substantially degraded above 0.2 cycles/mm. However, it should be noted that this traditional stochastic SNR figure of merit does not include the effect of structured anatomic noise from distant planes as well as noise from artifacts (the primary improvement seen with the plane-averaging approach).

FIG. 12. ENNPS for all planes in (a) a MITS reconstruction and (b) a MITSa7 reconstruction ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm).

IV.E. Simulated subtle pulmonary nodules in human chest tomosynthesis images

MITS and MITSa7 human chest data containing a digitally superimposed 5 mm pulmonary nodule in two different anatomical regions are shown in Figs. 15(a)–15(d). In the lung lateral to the left main bronchus [(a) and (b)] the MITSa7 reconstruction delivers enhanced clarity of the nodule by ameliorating partial-pixel artifacts which clutter the MITS image. The MITSa7 technique also renders a nodule overlying the mediastinum in the upper right lung [(c) and (d)] more clearly, even though the original MITS reconstruction is not degraded by noticeable partial-pixel artifacts in the area immediately surrounding the nodule. In both anatomic regions, the MITSa7 technique appears to visually reduce artifacts as well as stochastic variance, without any discernable loss in the displayed contrast of the simulated nodule.

V. DISCUSSION

Partial-pixel interpolation of image data and blurring functions generates low-contrast, low-frequency artifacts in some MITS images. In MITS imaging of the chest, partial-pixel artifacts originating from distant ribs are particularly confounding, creating horizontal striation patterns that obscure

low-contrast pulmonary vasculature (Fig. 6). Furthermore, near-plane anatomy takes on a low-pass filtered appearance in MITS images [Fig. 6(b)], and this partial blurring of near-plane anatomy can also be visually confounding.

Figure 6 shows that for MITS plane spacing of 5 mm, seven adjacent planes must be averaged before partial-pixel artifacts are sufficiently suppressed in MITS slabs. Although the averaging of seven planes would be expected to somewhat reduce contrast due to volume averaging, it can be seen that this technique actually substantially improves overall anatomical clarity.

Simulated MTF images in Fig. 8 suggest that distant low-frequency content is sometimes rendered in MITS planes, but these artifacts are not present in the MITSa7 MTF. Furthermore, the same MTF images illustrate that the MITSa7 MTF has a much more uniform thickness than the single-plane MITS MTF. This suggests that in MITSa7 images, anatomy is either shown in complete focus, or it is more completely smeared. The single-plane MITS MTF, on the other hand, demonstrates that the MITS slice thickness varies substantially with spatial frequency. Thus, in MITS, near-plane detail is partially low-pass filtered and will therefore be rendered somewhat blurred. The creation of MITS slabs does not appear to suppress nonlocal high-frequency artifacts which arise

FIG. 13. Seven-plane MITSa7 vs MITS ENNPS and MTF ratios for a centrally located plane ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm). The “expected ratio” of 1/7 is also plotted.

FIG. 14. MITSa7 vs MITS MTF and $\text{ENNPS}^{0.5}$ ratios for a centrally located plane ($\text{ANG} = 20^\circ$, $N = 71$, $\text{NP} = 69$, $\text{PSEP} = 4.4$ mm). Stochastic SNR is improved by the MITSa7 technique in regions where the MTF ratio is greater than the noise ratio.

FIG. 15. Simulated 5 mm pulmonary nodule digitally superimposed into human chest tomosynthesis data. The nodule is located near the left main bronchus in (a) a MITS reconstruction and (b) a MITSa7 reconstruction, and overlying the mediastinum in the upper right lung in (c) a MITS reconstruction and (d) a MITSa7 reconstruction. Tomosynthesis imaging parameters were $ANG = 20^\circ$, $N = 61$, $NP = 59$, $PSEP = 5$ mm.

when projections are spaced too coarsely to fully sample the scan angle.

Slice sensitivity profiles shown in Fig. 9 also illustrate the rendering of distant low-frequency information in MITS images. The same curves shown for MITSa7 in Fig. 10 show no substantial nonlocal information in the range 0.10–0.50 cycles/mm, and a fairly uniform effective slice thickness across all frequencies.

The in-plane MTF curves in Fig. 11 demonstrate that planes adjacent to the central MITS plane in a MITSa7 slab also contribute to the MITSa7 in-plane response, particularly at frequencies below 0.5 cycles/mm. Thus, while averaging adjacent planes strongly suppresses distant low-frequency artifacts, in-plane contrast is not affected as substantially.

Figures 12–14 confirm that stochastic variance is also reduced in MITSa7 images, and the stochastic SNR is improved between 0.05 and 0.20 cycles/mm as a result of the integration of signal (MTF) from adjacent planes when using the averaging technique. At higher frequencies, the improvement in ENNPS^{0.5} is outpaced by a loss in MTF due to volume averaging, and thus the stochastic SNR is not improved.

A more subjective appreciation of the image quality improvement due to MITSa7 which takes into account the artifact suppression capability of the averaging approach is attained by viewing the human chest tomosynthesis images in Fig. 7. Although the contrast and sharpness of small calcified nodules and a subcarinal lymph node are slightly reduced due to the afore-mentioned volume averaging, the MITSa7 image actually renders small low-contrast pulmonary vascu-

FIG. 16. Full pulmonary view of a MITSa7 reconstruction through the central chest of a human subject. Note the clarity of depicted anatomy, including lung vessels, aortic arch and central airways (trachea and proximal main bronchi), calcified subcarinal lymph nodes, and calcified left upper lobe nodules.

ature more visible than traditional MITS, due to the suppression of partial-pixel artifacts.

Figure 15 shows that MITSa7 also improves the visibility of small (5 mm) simulated nodules in human chest tomosynthesis data, both in the unobscured lung and in a region overlying the mediastinum, suggesting that the approach is robust and effective even in regions with low exposure and contrast.

A full human pulmonary view reconstructed with the MITSa7 technique is displayed in Fig. 16, and illustrates the clarity with which MITSa7 renders pulmonary anatomy, in its entirety.

VI. CONCLUSIONS

Results presented in this paper show that the MITSa7 technique ameliorates partial-pixel artifacts and reduces stochastic variance. Furthermore, as a result of the more uniform, yet thicker, slice-sensitivity profiles generated by MITSa7, near-plane anatomy is either fully rendered or almost entirely suppressed from view, rather than appearing partially “smeared” as it does in traditional MITS images. As a consequence of the averaging technique, high-frequency contrast and the high-frequency stochastic SNR appears to be reduced somewhat by the MITSa7 approach, but MITSa7 qualitatively improves the visualization of low-contrast, fine-detail pulmonary vasculature, as well as simulated small (5 mm), subtle pulmonary nodules. Given these results, we believe that the MITSa7 method is an improvement over traditional MITS for thoracic imaging and the pulmonary nodule detection task, and have selected the MITSa7 approach for use in all future research using MITS at our institution.⁴

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